

Problems in texture analysis with magnetic resonance imaging

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Since its introduction in the 1980s, magnetic resonance imaging (MRI) has become recognized as a powerful in vivo diagnostic tool. The objective of this article is to discuss developments in quantitative MRI—and particularly texture analysis—that maximize diagnostic information. A fundamental part of the work involves careful study of the optimal MRI data collection strategies for texture analysis. This is critical, because different centers may vary their measuring sequences and acquisition protocols for clinical reasons, and may be reluctant to vary these for texture investigation. Different measuring techniques, such as spin echo, gradient echo, and echo planar, and different measuring parameters produce totally different patterns in texture. Careful investigation of the dependence of all these variables using texture phantoms (test objects) will help understand how MRI image texture is formed from tissue structures. Therefore, it is essential to design and test reliable and accurate test objects for a detailed assessment of texture analysis methods in MRI. The main feature of these test objects is their ability to simulate tissue-like textures with tissue-like MR relaxation properties. Long-term stability is also vital, as is uniformity of the overall texture. Another aspect is to examine the test objects under a whole range of MRI measuring sequences and imaging conditions using different scanners to determine their stability and utility.

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Dialogues Clin Neurosci. 2004;6:235-242.

Magnetic resonance imaging (MRI) is one of the most exciting imaging technologies for texture analysis: it offers the best soft tissue contrast, which can be dramatically varied during imaging. Careful study of the dependence of texture parameters on MRI data collection strategy is essential for texture analysis in order to avoid artificial texture from the scanner. This is critical, since different centers may vary their measuring sequences and acquisition protocols for their clinical investigations.

The basic problem in quantitative MRI texture analysis is the large number of different measuring techniques and imaging parameters, which can be easily changed during a clinical examination. Thus, different techniques and imaging parameters produce totally different patterns in the texture parameters of the same tissues in clinical examinations with different sensitivity to artificial texture overlaid by the scanner. The main problem in texture analysis with MRI is to avoid this artificial texture and minimize its influence. The presented work was performed in the framework of a European research project COST (Cooperation in the Field of Scientific and Technical Research) B11 between 1998 and 2002 by institutions from 13 European countries, aimed at the development of quantitative methods for MRI texture analysis.¹ For further detail of texture analysis, parameters, and software, see the article by Materka in this volume² or references 3 to 7.

Keywords: texture analysis; magnetic resonance imaging; brain; trabecular bone

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This article is published following the 14th Biological Interface Conference held in Rouffach, France, between October 1 and 5, 2002, on the theme of "Drug Development." Other articles from this meeting can be found in *Dialogues in Clinical Neuroscience* (2002, Vol 4, No 4).

Selected abbreviations and acronyms

EPI	<i>echo planar imaging</i>
FLASH	<i>fast low angle shot</i>
FOV	<i>field of view</i>
MA	<i>matrix size</i>
RF	<i>radio frequency</i>
ROI	<i>region of interest</i>
SNR	<i>signal-to-noise ratio</i>
TE	<i>spin echo time</i>
TH	<i>slice thickness</i>
TR	<i>repetition time</i>

Material and methods

The complexity of this problem can be demonstrated by considering a typical measuring spin echo sequence as measured by a commercial whole-body imager. Various parameters can be easily changed during clinical investigation: image contrast is mainly defined by repetition time (TR) and spin echo time (TE); image resolution is defined by slice thickness (TH), field of view (FOV), and matrix size (MA), which also influence texture analysis. The parameters of k-space acquisition and reconstruction are very important: k-space is the artificial space in which the raw MRI data are collected, and the image contrast and texture is very sensitive to k-space strategies. Other parameters like coil setup and number of active coil segments are also responsible for signal and flip angle (α) variations in the image. Careful investigation of the dependence of all these variables will help understand how MRI image texture is formed in tissue structures. In our studies, MRI acquisition was performed in the standard head coil of a 1.5-T scanner (Siemens Vision, Erlangen, Germany).

Spin echo technique

One of the most important measuring techniques in clinical diagnosis is the spin echo sequence, in which 90° and 180° radio frequency (RF) pulses produce the spin echo signal. In addition, gradients are used in x, y, and z directions to localize the signal.⁸ The advantages of this technique are reduced artifacts, clearly defined contrast, and common availability. The disadvantages are the contrast dependency on RF pulse quality, and slice cross-talking, which is typical of a two-dimensional (2D) technique. This imaging technique allows measurement of the three relevant MRI tissue parameters: spin density (ρ), spin-lattice relaxation time (T_1), and spin-spin relaxation time

(T_2), which are most responsible for tissue contrast and texture. According to the theoretical equation for the spin echo signal⁹:

$$S \approx \rho \cdot (1 - e^{-TR/T_1}) \cdot e^{-TE/T_2} \quad [1]$$

in which S is the spin echo signal, the contrast ρ can be created by a long TR and short TE, resulting in a flat image contrast and texture at high signal intensity (*Figure 1a*). T_1 contrast can be created by short TR and short TE in spin echo imaging (*Figure 1b*). On the other hand, T_2 contrast is created by long TR and long TE, mainly reflecting the water content of the tissue (*Figure 1c*). These three physical tissue parameters are described in reference 1. The real physical properties of tissues may be obscured by artificial contrast and texture from the scanner.

Slice profile

Slice profile is defined by the slice gradient and the shape of the RF pulse. Ideally, we would like to measure a rectangular slice, but due to technical reasons the real slice profile is Gaussian shaped. The consequence is that we have signal contributions from neighboring slices that influence the tissue texture. To minimize this effect, an interleaved slicing scheme is used in multislice 2D imaging.

k-space

Another aspect of artificial texture is connected to the k-space, which describes the strategy for raw data collection. The k-space contains the measured signal frequencies k_x and k_y , the so-called hologram from which the real MRI image can be calculated by a Fourier transform

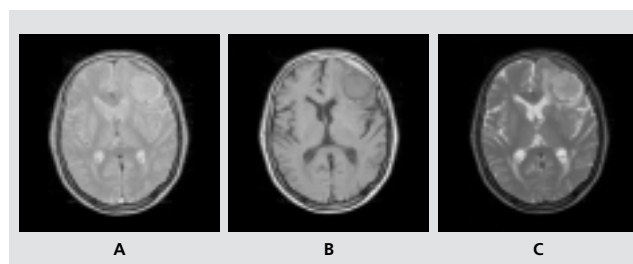


Figure 1. Spin echo images of a patient with meningioma. A. p-image (TR/TE = 2000 ms/10 ms). B. T_1 image (TR/TE = 600 ms/10 ms). C. T_2 image (TR/TE 2000 ms/100 ms). TR, repetition time; TE, spin echo time.

(Figure 2). Some imaging techniques measure only every second line in the k-space to speed up the imaging sequence, which results in a reduction in the signal-to-noise ratio (SNR) by $1/\sqrt{2}$ and aliasing artifacts, with consequences for image texture. Restriction to the center of the k-space with zero filling of the outer part results in the same SNR effect without aliasing.

RF excitation

Another important variable is the RF characteristic and sensitivity of the transmitting and/or receiving coil, which can produce a lot of artificial texture from the scanner. This is demonstrated in Figure 3 using hard image scaling, which shows a clear signal inhomogeneity due to nonideal RF pulses at the outer range of the phantom (ie, coil). Another coil effect on image texture is produced with coil arrays, where the summarized image is a result of the combination of single coils, each of which contributes its own coil characteristics (eg, SNR, sensitivity, and RF excitation profile) to the summarized image. This means that image texture could slightly differ between the object center and the object boundary, where protons are close or far away from the center of the coil.

Gradient echo techniques

Significant effects on image contrast and texture are introduced by the imaging sequence itself, since the imaging signal can have a very complex dependence on the physical properties of the underlying tissue. One example is the so-

called gradient echo technique like FLASH (fast low angle shot),¹⁰ where the 90° and 180° RF pulses are replaced by a low-angle RF pulse with a bipolar gradient scheme resulting in a gradient echo signal. This measuring technique can be used as fast imaging 2D technique or as a real 3D imaging technique because of the compact timing of the sequence. On the other hand, the FLASH signal has a complex dependence on T_1 , the local spin-spin relaxation time (T_2^*), and the flip angle α , according to:

$$S \approx A \cdot e^{-TE/T_2^*}$$

$$\text{with } A = \rho \cdot \sin \alpha \cdot \frac{1 - e^{-TR/T_1}}{1 - \cos \alpha \cdot e^{-TR/T_1}} \quad [2]$$

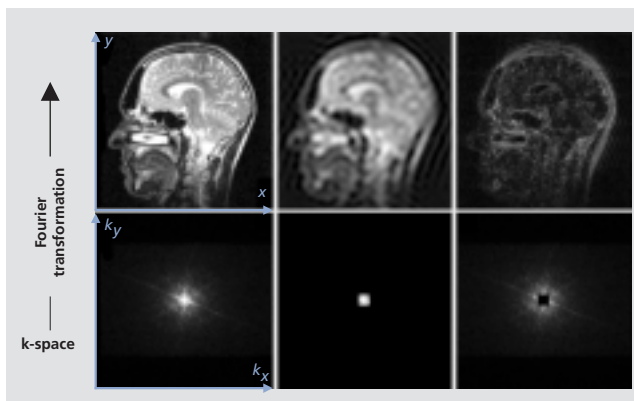


Figure 2. The effect of k-space filling on image contrast and texture. The example demonstrates the strong dependence of image texture on the k-space filling factor as used in so-called "keyhole" techniques.

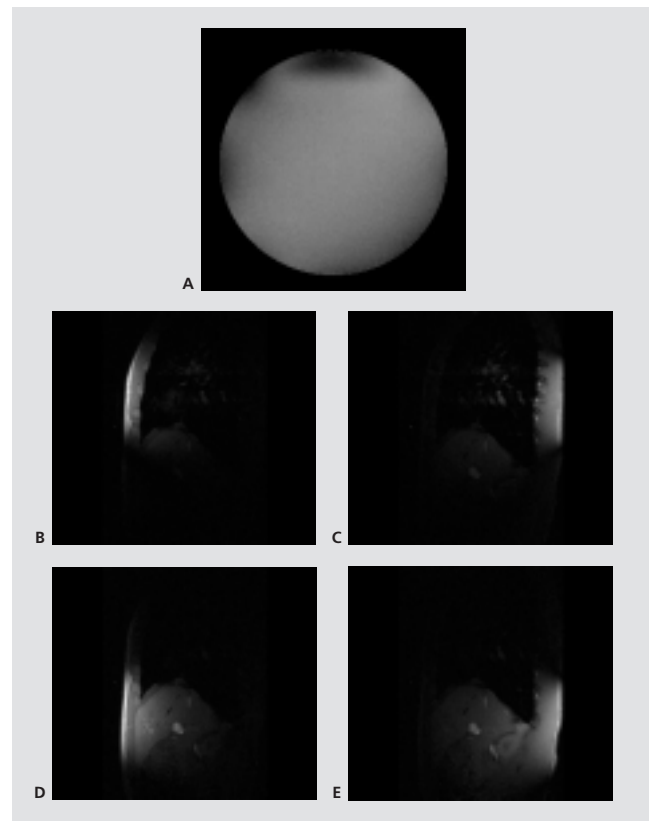


Figure 3. Effect of radio frequency (RF) profile of the head coil on image contrast and texture. **A.** Phantom measurement demonstrating the signal inhomogeneity due to nonideal RF pulses at the outer range of the image (ie, coil). **B** to **E.** Result of a measurement using coil arrays, where the summarized image is a result of the combination of the single coils, which contribute with their own coil characteristic (signal-to-noise ratio, sensitivity, and RF excitation profile) to the contrast and texture of the image.

Thus, the different flip angle distributions produced by the coil characteristics result in different signals, and as a consequence in different image texture patterns as demonstrated in *Figure 4*.

A very complex signal and texture situation is present in so-called single shot imaging techniques like echo planar imaging (EPI),¹¹ where k-space is filled in one shot with multiple gradient echoes. This is achieved by a gradient scheme in which the upper corner of the k-space is reached by a single gradient pulse followed by a series of blips resulting in a rectangular movement through the k-space. This technique is very sensitive to local susceptibility artifacts, resulting in image distortions and strong T_2^* contrast dependence.

Some special imaging techniques like spiral imaging can produce a very complex pattern in the image texture, since this single shot technique moves on a spiral through the k-space, which can be achieved by oscillating gradients with a phase shift of 90° in the x and y directions. This technique requires data interpolation in k-space to bring the measured data onto a Cartesian coordinate system before Fourier transform. This interpolation can produce spurious artifacts with the consequence that the image texture is dependent on k-space interpolation and image reconstruction. In addition, the problem of texture dependence on measuring technique is more complicated

due to the large number of imaging sequences available on modern scanners, as illustrated in *Figure 5*.

Results and discussion

SNR dependence

Figures 6a and 6b show the results of a FLASH experiment in a normal volunteer for SNR dependence measurement of texture parameters. The measuring parameters of the FLASH experiment were: $TR/TE/\alpha = 2 \text{ ms}/9 \text{ ms}/30^\circ$; bandwidth (BW) = 195 Hz/pixel; MA = 512×512 ; FOV = 280 mm; TH = 2 mm; and acquisitions (AQ) = 1 to 324 resulting in an SNR = 1 to 18. Texture parameters (SNR, entropy 5×5 , correlation 5×5) of white matter, gray matter, and noise are shown as a function of the number of acquisitions ($=\text{SNR}^2$). *Figure 6c* demonstrates that no texture can be measured in white matter using standard image resolution ($0.5 \times 0.5 \times 2 \text{ mm}^3$) as described above, since the SNR of white matter has the same characteristics as noise. In contrast, the SNR of gray matter reaches a nearly constant value at about 16 acquisitions and no further improvement can be reached due to the true underlying texture of the tissue. The same observation holds for a typical parameter of microtexture, like entropy 5×5 (*Figure 6d*), while no dependence

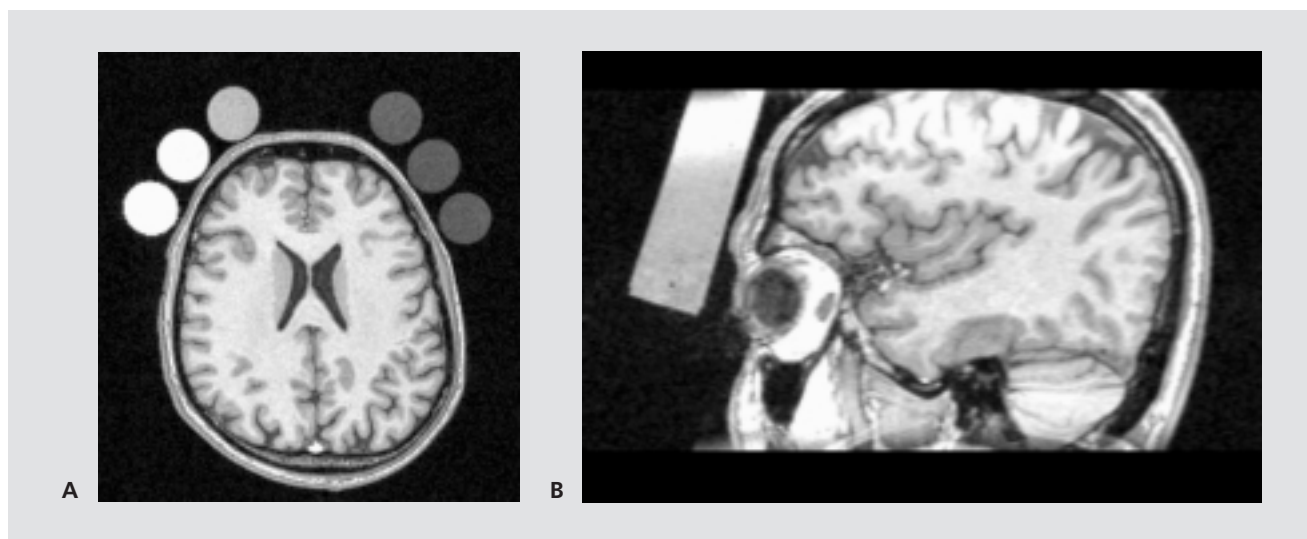


Figure 4. Example of a 3D FLASH (fast low angle shot) dataset of a normal volunteer measured by the conventional head coil. **A.** Excellent T_1 contrast in the original transversal images. **B.** A strong signal inhomogeneity is obvious in the reconstructed sagittal images as seen in the homogeneous phantom and corresponding anatomical structures, like upper part of the brain and cerebellum. This artifact is due to the radio frequency excitation profile of the head coil, which produces different T_1 weightings and signal amplitudes as a function of the flip angle according to the FLASH formula (*Equation 2*).

on SNR can be detected for a typical parameter of macrotexture, like correlation 5×5 (Figure 6e). Based on this observation, a sufficient $\text{SNR} > 4$ is necessary to measure the real textural behavior of the human brain.^{12,13}

Normalization

A texture test object (PSAG) was developed on the basis of polystyrene (PS) and agar solution (AG) to mimic texture properties artificially. PS spheres are available from the technological process of PS production. Two types of spheres were used for the phantom construction: randomly distributed spheres of diameter 0.2 to 3.15 mm; or mechanically separated spheres of diameter 0.8 to 1.25 mm, 1.25 to 2 mm, or 2 to 3.15 mm. Polyethylene tubes of diameter 1.5 and 2.8 cm were filled with spheres and by

a hot solution of 4% agar (free and doped with DyCl_3). One milliliter of 0.1% NaN_3 was added per liter of agar for microbiological stability.¹⁴

A second texture test object containing foam at different densities in Gd-DTPA solution was used to describe microtexture properties. Phantom tubes containing foams with coarse, middle, and fine density were constructed and filled with a Magnevist® (Schering, Berlin) solution at a concentration of 1:4000. Problems with the foam phantoms are air bubbles, which create susceptibility artifacts in the images, and so a careful preparation of the foam phantoms is necessary. Both types of phantoms were placed next to the head of a volunteer and a position for the imaging slab was chosen such that all vials and part of the volunteer's brain were contained in the 3D slab. With this setup several 3D data sets with different imaging parameters were

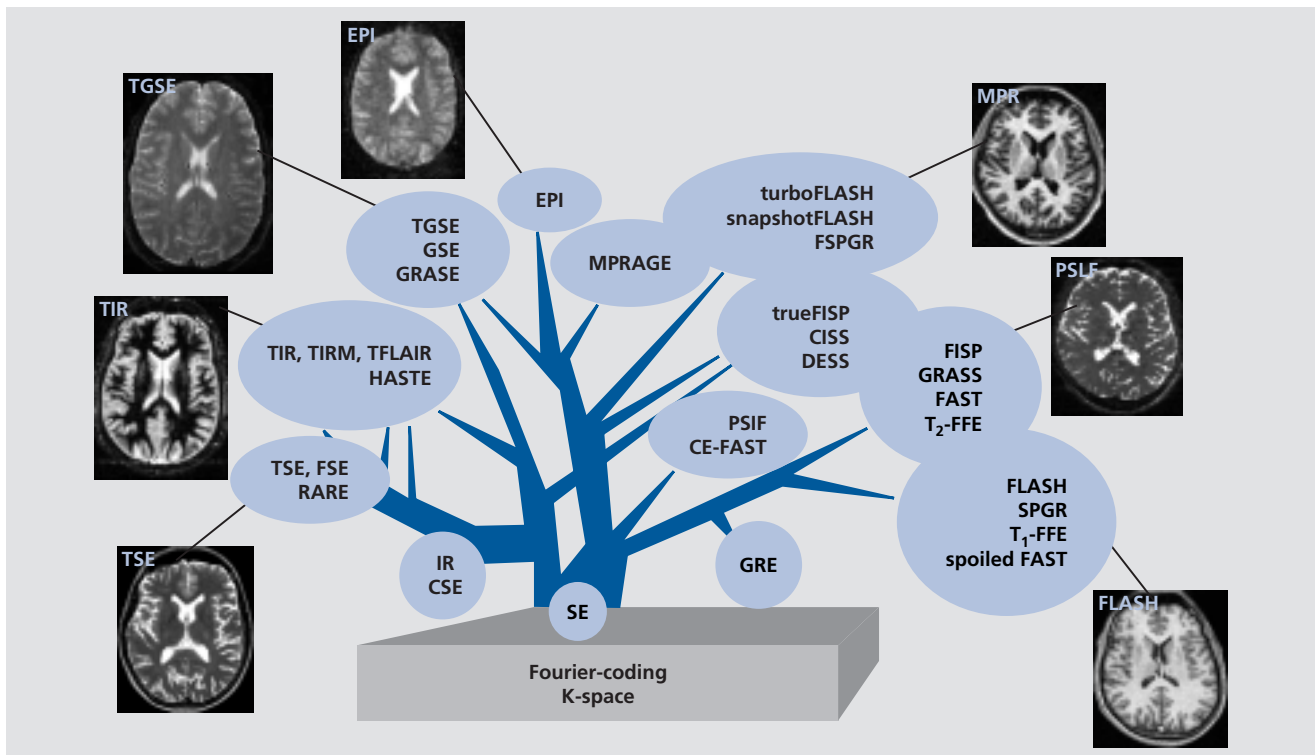


Figure 5. Sketch of the family of imaging techniques available on modern scanners. There are many strategies of mixing spin echoes with gradient echoes to speed up imaging time with the consequence of very complex image contrast and texture. CISS, constructive interference in the steady state; CSE, conventional SE; DESS, dual echo steady state; EPI, echo planar imaging; FAST, Fourier-acquired steady state; FISP, fast imaging with steady precession; FLASH, fast low angle shot; FSE, fast spin echo; FSPGR, fast spoiled gradient recalled acquisition into steady state; GRASE, gradient and spin echo; GRASS, gradient recalled acquisition into steady state; GSE, gradient SE; HASTE, half-Fourier acquisition single-shot turbo SE; IR, inversion recovery; MPRAGE, magnetization prepared gradient echo imaging; RARE, rapid acquisition with relaxation enhancement; SE, spin echo; SPGR, spoiled gradient recalled acquisition into steady state; T1-FFE, T1-weighted fast field echo; T2-FFE, T2-weighted fast field echo; TFLAIR, turbo fluid attenuated IR; TGSE, turbo GSE; TIR, turbo IR; TIRM, turbo IR magnitude; TSE, turbo SE.

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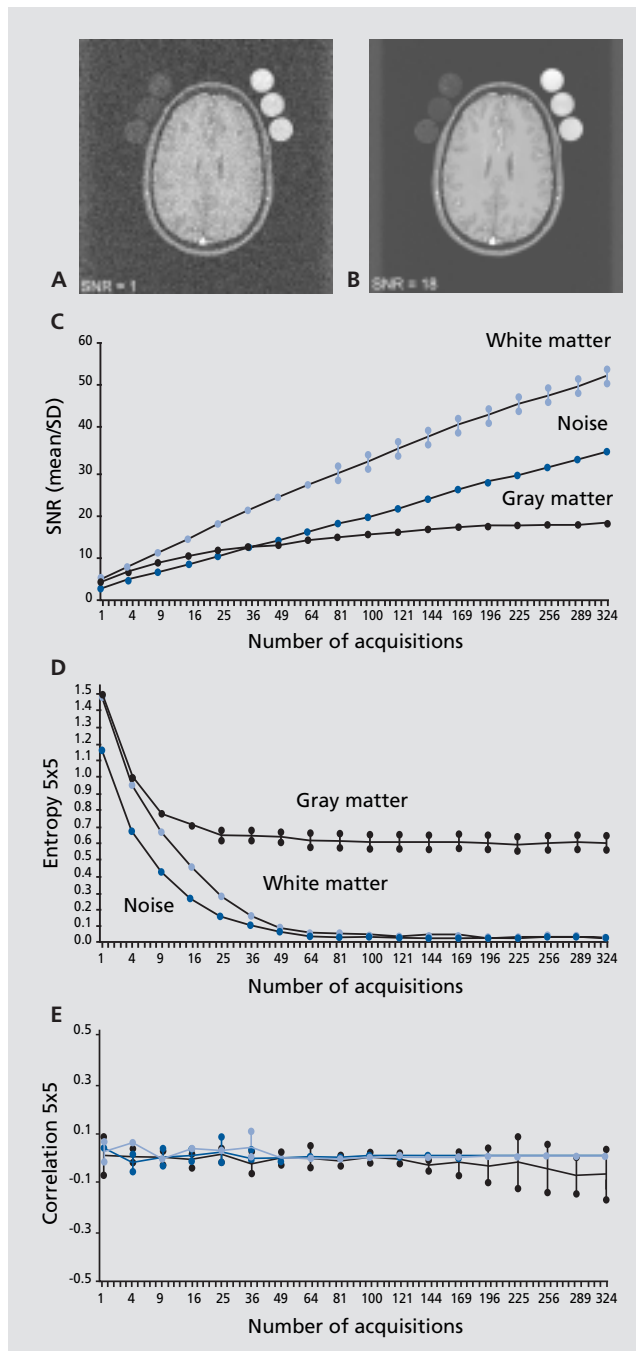


Figure 6. FLASH (fast low angle shot) images of a normal volunteer for measuring signal-to-noise (SNR) dependence of texture parameters at (A) SNR =1 (1 acquisition) and (B) SNR =18 (324 acquisitions). C to E. Texture parameters (SNR, entropy 5x5, correlation 5x5) of white matter, gray matter, and noise are shown as a function of the number of acquisitions (=SNR²). SD, standard deviation.

acquired to demonstrate the influence of resolution and SNR, as well as the dependence of the texture parameters on different imaging parameters (eg, α , TR, TE). In a pilot study, texture parameters such as mean gradient show the same behavior in phantoms as in white matter for different patients, indicating that a normalization of texture parameters using test objects is possible (Figure 7). However, texture normalization is necessary, but it is not possible to mimic all texture features by phantoms.¹⁵

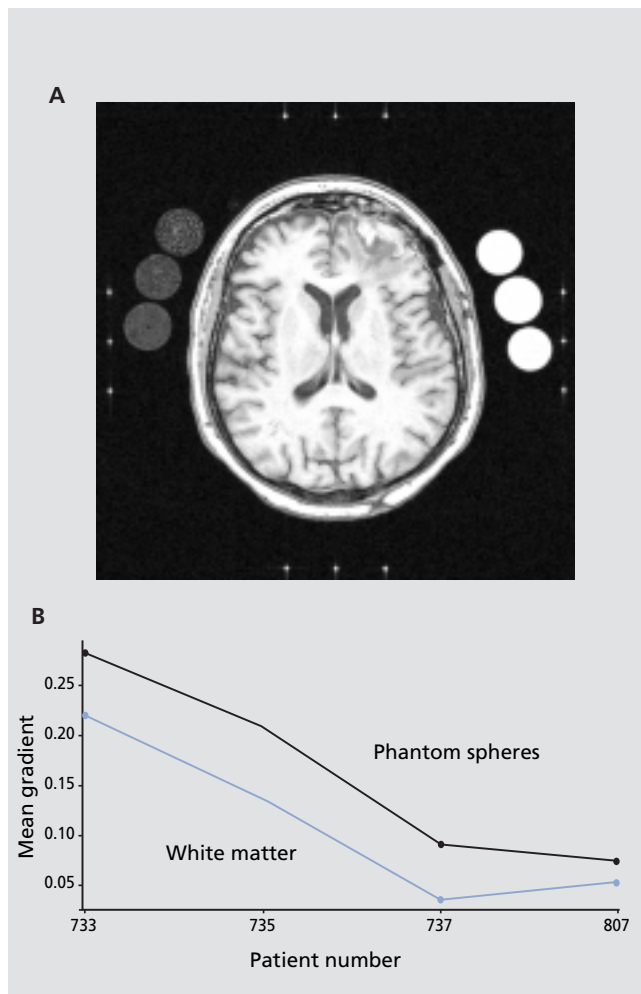


Figure 7. A. Three-dimensional FLASH (fast low angle shot) image of a patient with glioblastoma with texture test objects located beside the head for testing texture normalization. B. Texture parameters such as mean gradient show the same behavior in the phantom as in white matter for different patients, indicating that normalization of texture parameters using test objects is possible.

Clinical application

The aim of this pilot study was to assess the possibility of quantitative description of texture directivity in trabecular bone with an attempt to quantitative description of trabecular bone structural anisotropy using texture analysis of 3D FLASH MRI. A series of 3D FLASH images, all of 256×256 pixels, with the voxel size of $0.4 \times 0.4 \times 0.4 \text{ mm}^3$, were measured on a standard 1.5-T scanner (Siemens Vision, Erlangen, Germany) using a small flex coil. The images in *Figure 8* represent trabecular bone cross-sections in the sagittal and reconstructed transversal direction. For bone image texture analysis, circular regions of interest (ROI) were marked on corresponding bone cross-sections and effort has been made

to maintain a large-size ROI for better statistical significance of texture parameters. The texture of the bone image shows apparent directivity, which reflects anisotropy of its physical structure according to the direction of gravity (*Figure 8c*). Quantitative analysis of this directivity is important to medical diagnosis, eg, in early detection of osteoporosis, as the directivity may vary according to the development of the disease. □

The author like to thank Michael Bock (DKFZ Heidelberg, Germany), Milan Hajek (University Prague, Czech Republic), Richard Lerski (University Dundee, Scotland), Arvid Lundervold (University Bergen, Norway), Andrzej Materka (University Lodz, Poland), Lubomir Pousek (Technical University Prague, Czech Republic), Yan Rolland (University Rennes, France), and Ivan Zuna (DKFZ Heidelberg, Germany) for their help during the COST B11 action in many aspects of texture measurements and analysis.

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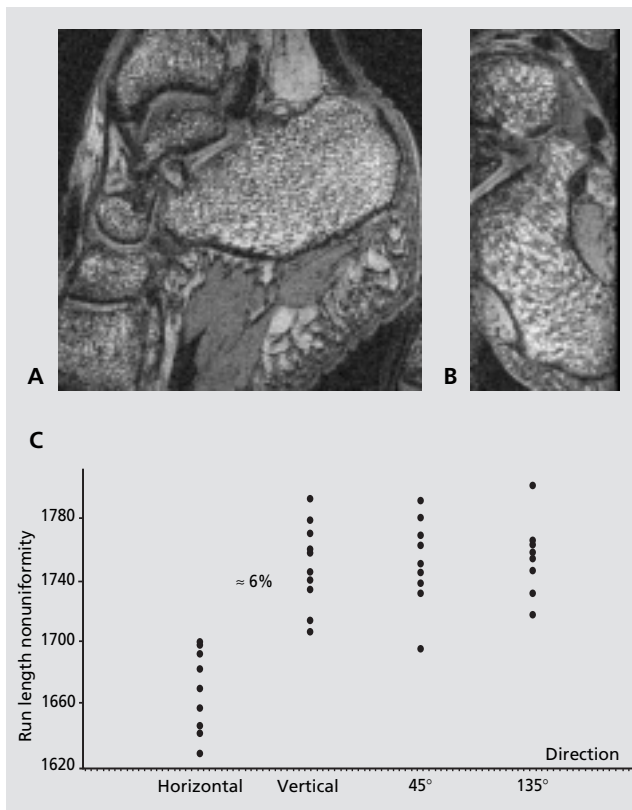


Figure 8. Example of a trabecular bone 3D FLASH (fast low angle shot) measurement of a normal volunteer in sagittal (A) and reconstructed transversal direction (B) for testing texture directivity. (C) Texture parameters like run length nonuniformity show a clear dependence on direction of gravity. Quantitative analysis of this directivity is important to medical diagnosis, eg, in early detection of osteoporosis, as the directivity may vary according to the development of the disease.

Problemas en el análisis de la textura con imágenes de resonancia magnética

Las imágenes de resonancia magnética (IRM) se han reconocido como una poderosa herramienta para el diagnóstico in vivo desde su introducción en la década de 1980. El objetivo de este artículo es discutir el desarrollo de las IRM de tipo cuantitativo y en particular el análisis de la textura, lo que permite maximizar la información para el diagnóstico. Una parte fundamental de este trabajo incluye un cuidadoso estudio de las mejores estrategias de recolección de datos de las IRM para el análisis de la textura. Este aspecto es central ya que diferentes centros, por razones clínicas, pueden variar la secuencia de medición y los protocolos de adquisición de datos y por lo tanto pueden ser reacios a modificar éstos para la investigación de la textura. Diversas técnicas de medición como el eco de spin, el eco de gradiente y el eco planar y distintos parámetros de medición producen patrones de textura totalmente diferentes. Una investigación cuidadosa de la influencia de todas estas variables mediante el empleo de texturas fantasma (objetos de prueba) ayudará a comprender cómo se forman las texturas de las IRM a partir de las estructuras de los tejidos. Por lo tanto, resulta esencial diseñar y ensayar objetos de prueba exactos y confiables que permitan una evaluación detallada de los métodos de análisis de la textura de las IRM. La característica principal de estos objetos de prueba es su capacidad para simular texturas parecidas a los tejidos y con propiedades semejantes a estos últimos. La estabilidad a largo plazo de estos modelos es de gran importancia, como también la uniformidad global de la textura. Otro aspecto consiste en examinar la estabilidad y utilidad de los objetos de prueba mediante diversas secuencias de medición y condiciones en que se realicen las IRM empleando distintos resonadores.

Problèmes posés par les analyses de texture au cours de l'imagerie par résonance magnétique

Depuis son introduction au milieu des années quatre-vingt, l'imagerie par résonance magnétique (IRM) est devenue un puissant outil de diagnostic in vivo. L'objectif de cet article est d'évaluer les avancées de l'IRM quantitative, notamment en ce qui concerne les analyses de texture, qui optimisent l'information diagnostique. Cet article sera en grande partie consacré à l'étude minutieuse des meilleures stratégies de recueil de données d'IRM pour les analyses de texture. Ceci est essentiel, dans la mesure où les séquences de mesures et les protocoles de saisie cliniques peuvent varier selon les centres et que ces derniers peuvent être réticents à les modifier pour les analyses de texture. Des différences aussi bien dans les techniques de mesure utilisées, qu'il s'agisse de l'écho de spin, l'écho de gradient, l'écho planaire, etc., que dans les paramètres mesurés retentissent sur la texture en entraînant l'apparition de motifs totalement différents. L'évaluation précise de l'influence de ces variables en utilisant des images étalon (« fantômes ») de texture (ou objets de test) facilitera une meilleure compréhension du mode de constitution des textures des structures tissulaires en IRM. Par conséquent, il est essentiel de développer et d'expérimenter des objets de test exacts et fiables pour une évaluation détaillée des méthodes utilisées en IRM pour les analyses de texture. La principale caractéristique de ces modèles réside dans leur capacité à imiter des textures semblables à celles produites par les tissus et ayant des propriétés de relaxation RM identiques. La stabilité à long terme de ces modèles revêt également une grande importance, tout comme l'uniformité globale des textures qui en résultent. Un autre objectif est d'examiner la stabilité et l'utilité de ces objets de test en les soumettant à toute une gamme de séquences de mesures et de conditions d'imagerie par IRM et de les étudier avec divers types d'appareils d'IRM.